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ARTICLE

Influence of Unmanned Aerial Vehicle (UAV) Payloads and Flight Speeds on Pesticide Droplet Deposition: Indoor Testing Rig Study

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Abstract

This study aims to determine droplet deposition resulting from dynamic change in payloads and flight speeds of Unmanned Aerial Vehicle (UAV) during operation. The study was conducted at Universiti Putra Malaysia, Serdang, Malaysia. The Advansia A1 hexacopter was first set to fly at combinations of 3 payloads (3.3, 6.6, and 9.9 kg) with 3 flight speeds (3, 5 and 7 m/s) to collect individual rotor RPM, which will later be used to set the rotors' speed during indoor testing experiment. During the experiment, actual pesticide (Alosa EC) was used at 0.5 % concentration in the spray deposition test. The droplet deposition sample was collected using water-sensitive paper and analyzed with DepositScan software. Result obtained showed that the droplet size, number of droplets per area and deposition rate were significantly affected by the UAV's flight speed at a significant level of $P < 0.05$, with all the deposition characteristics tested reduced as the flight speed increased. Due to the travelling pattern of the UAV, the amount of deposition during the accelerating and decelerating phases was found to be 2 to 8.5 times higher compared to the amount of deposition during the stable phase. As a conclusion, the travelling pattern of UAV varied with the flight speed along the pathway, which had an effect on the deposition rate. The obtained finding is remarkable, critical and useful in managing UAV and improving the spraying deposition.

Keywords: Spraying UAV, UAV payload, UAV flight speed, UAV travelling pattern, Deposition characteristic

1. Introduction

Pesticide application technology is essential in pest management. The selection of appropriate equipment and application techniques are crucial to the success of any pest control operation. Even if a high-quality pesticide is used at the appropriate time, the treatment may not be effective if it is not applied correctly. Therefore, to ensure quality pesticide application, the primary

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objective of any pesticide spraying technology is to reach the target uniformly with the correct dosage, proper size and right density.

Undoubtedly, the biggest challenge in agricultural chemical spraying is to achieve optimal application technique in order to meet the spray target at the determined application rate with minimal drift (Grzegorz, 2013). Several experiments were undertaken to determine droplet deposition via UAV spraying. Shilin et al. (2017) discovered that pesticide spraying by UAV has low precision and inadequate quality. Droplet deposition patterns were discovered to be scattered in both lateral and longitudinal orientations. This work confirmed previous findings by Qin et al. (2016) and Hanxin (2016), who studied spray deposition from UAVs in citrus and paddy crops. It was also noted that the use of UAVs in spraying added another factor in which the effect of air flow or downwash produced by rotational rotors caused the droplets to drift in all directions in an uncontrollable manner, affecting the deposition pattern and resulting in pesticide waste (He et al., 2017; Ismail et al., 2021; Shilin et al., 2017).

Understanding the behavior and how the technology works in the first place are critical as a basis for managing and handling pesticides and calibrating the equipment. It needs to be understood that, while the UAV is spraying across the field: i) the payload is reduced, and ii) due to the nature of UAV, it experience different phases and speeds. These two factors would influence the rotors' RPM and in addition to application parameters, it is expected to produce variations in airflow and droplet deposition. Ismail et al. (2021) found that RPM of each rotor blade decreased by 14–20 % as the payload decreased from 10 to 0 kg, consequently producing a downwash airflow pattern that constantly varies from the starting point up to the finishing point during spraying. Travelling pattern of the UAV and flight speed set by the operator were also found to be significant factors. Due to the accelerating and decelerating phases, the percentage distance of UAV flying at the speed set by the operator decreased as the speed increased. Without proper management and variable rate in spraying UAVs, the droplet deposition is expected to vary along the spraying line (Ismail et al., 2021).

Thus, as a continuation of previous works, the objective of this study is to quantify droplet deposition at various UAV payloads and flight speeds using an indoor testing facility. It should also be noted that, in this study, as the UAV was mounted on a rig, RPM of the UAV blades were unable to respond to the change in payload and flight speed. Thus, to create an actual airflow for each combination of treatment, data of the blades' RPM was first collected in field and will be used to set up the blades during experiment using the testing facility.

2. Materials and methods

2.1. UAV specification

In this investigation, an agricultural hexacopter UAV with a maximum payload of 10 kg was used (Fig. 1).

2.2. Data collection on blade's revolution per minute (RPM)

The UAV was flown in six straight route replications in field with different combination of flying speeds (3, 5 and 7 m/s) and payloads (3.3,6.6 and 9.9 kg). In all tests, the UAV's height was set to 2.5 m. The data was collected between 6:30 a.m. and 8:30 a.m., with wind speed measuring between 2 and 3 km/h (calm). At such climatic conditions, it is relatively easy to maintain the UAV's flying stability while also imitating the actual operation of pesticide spraying under minimum spray drift.

2.3. Data extraction

Data were retrieved from the flight controller using in-house built interface integrated with Super-X software provided by the UAV supplier. For every combination of payload-speed stated in Section 2.2, throttle percent data for each rotor were extracted and converted to RPM using Eq. (1) derived from the data supplied by the manufacturer as below:

$$Y = -0.1971\,x^2 + 52.65\,x + 2106 \qquad \text{Eq.1}$$

where;

Y = Motor rotational speed, RPM

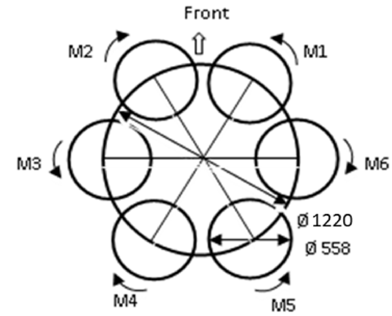
X = Motor throttle level, %

2.4. Experiment using indoor testing facility

2.4.1. Indoor testing facility

The indoor UAV testing facility was developed mainly to quantify the spraying deposition using water-sensitive papers (spray width, droplet size (μm), number of droplets per area and spray deposit volume (μL/cm^2)). In order to get the same airflow profile and deposition effects, the facility was developed to emulate the actual operation conditions of the tested UAV in the field. An indoor facility was chosen to allow better control of the

(a)



(b)

Fig. 1. (a) Picture of actual UAV, (b) Diameter (mm) of propellers and wheelbase of UAV.

UAV traveling path and at the same time, to overcome any environmental disturbance that may affect the UAV spray deposition. The overall length and height of the facility were approximately 23 m and 4.5 m, respectively. The schematic diagram and developed facility are shown in Figs. 2 and 3.

The testing facility has two main sections. The first section consists of a rail support structure and its driving unit. Attached to the beam of the rail support structure was a moving carriage that was used to mount the UAV. The height of the mounting frame could be adjusted at three tested height levels (1.5 m, 2.5 m and 3.5 m from the ground) while the forward speed of the moving carriage can be regulated at maximum of 10 m/s. The required test flight heights and speeds were set accordingly prior to the evaluation test. The frame structure was used to secure the UAV onto the moving carriage.

The second section was a sampling platform structure and its adjusting height unit to cover the total sampling area for spray deposition. The sampling platform was constructed to have a total of 49 sampling points and at each of these point, a sample holder stand was placed to hold a water-sensitive paper.

2.4.2. Treatment

The droplet deposition samples were collected at a combination of three flight speeds (3, 5 and 7 m/s) and payloads (3.3, 6.6, and 9.9 kg) which represent near-empty, half-tank, and full-tank conditions. This resulted in nine treatments, each replicated three times.

2.4.3. UAV blade's RPM setting

In order to obtain accurate downwash and deposition data of the UAV using the developed testing facility, the UAV blades' rotational speed were set to be similar to the rotational speed during actual flight

Fig. 3. Actual indoor UAV testing facility.

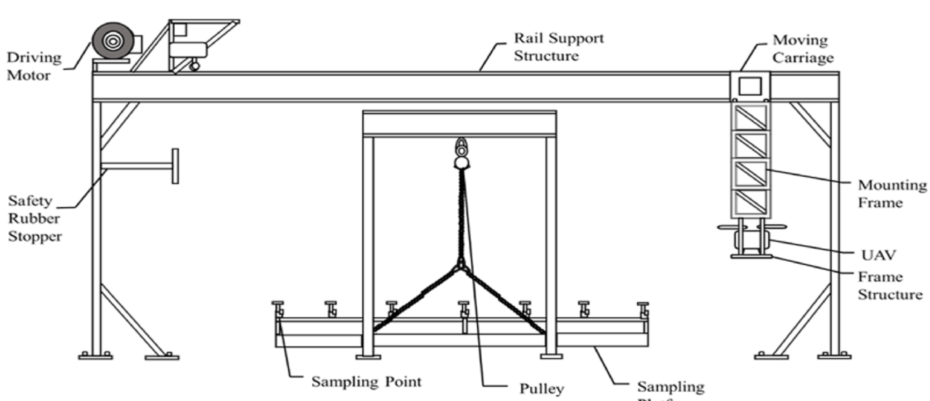


Fig. 2. Schematic diagram of the indoor UAV testing facility.

operation. To do so, a field test was carried out beforehand to obtain the rotational speed data of each UAV blade (Section 2.2). The setting was then executed by bypassing the flight controller and instead connecting to the ESC of each motor straight to the receiver and external power source. In this study, two motors were connected to the servo channels of one receiver, where one transmitter controlled the speed of said motors. Thus, for the hexacopter, 3 transmitters were used. The list of electronics parts used is provided in Table 1. Throughout the tests, the spray pump connection stayed connected to the flight controller and was activated or stopped using the UAV controller (Fig. 4).

While setting the speed of the blade using a transmitter, the rotational speed of the blade could be checked or revised using wireless tachometer that was fixed near the blade. Wireless tachometer of the Arduino IR sensor has the ability to read at a maximum of 10,000 rpm and it is located close to the rotating motor. Reading from the sensor was sent to the receiver every 0.5 s via radio frequency (RF). The receiver, on the other hand, was connected to the computer via USB port, so that the reading of rotational speed sent by the sensor can be directly displayed via the computer using Arduino Ide software (serial monitor). The process of receiving and setting the rotational speed of the blades is shown in Fig. 5.

2.4.4. *UAV and sampling grid point setting*

The experiments were conducted using an indoor testing facility. The speed of moving carriage was set to be similar with flight speed in treatments. The height of the UAV was maintained at 2.5 m from the ground. Spray was applied using four flat-fan green nozzles (110° angle, 0.57 L/min flow rate each), vertically downward. A total of 28 water sensitive papers (19 mm × 26 mm) were used as the deposition collector. The water sensitive papers were arranged at the distance of 1 m × 2 m on a 6 m × 6 m sampling platform that brings a total of four horizontal lines. The test was replicated three times (Figs. 6 and 7).

Table 1. List of electronic parts used for independent blades' speed controller.

Parts	Unit	Model/Specification
UAV brushless motor	6	R9 JMR6215 – KV170
Electronic Speed Controller (ESC)	6	X-rotor Pro KV80A
LiPo rechargeable battery pack	3	11.1 V 3s 25C 3000 mAh
Receiver	3	FS - iA10B
Transmitter	3	Fly Sky i6X

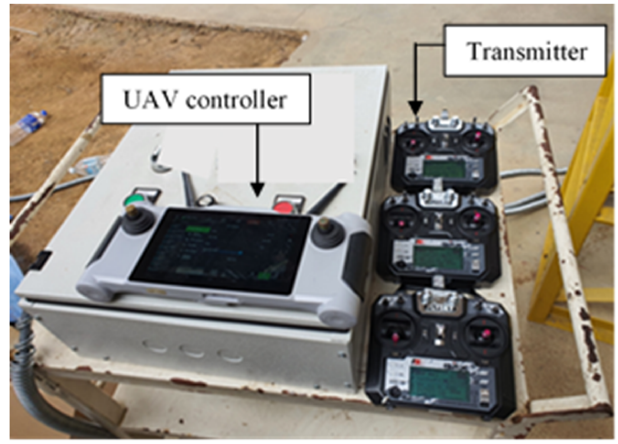


Fig. 4. Three transmitters were used to regulate rotational speeds of the six blades and one UAV controller to activate/stop the spray pump.

2.4.5. *Evaluation of spray droplet deposition*

All of the 28 water sensitive papers (WSPs) were carefully collected with tweezers after 5–10 min of test. The collected WSPs were then scanned using Epson Printer. The images were saved at 8-bit, 600 dpi of resolution as TIF image format and evaluated using the DepositScan software (USDA, USA) (Zhu et al., 2011). Result from the various speeds and payloads will be studied via characteristics of the droplet deposition collected with respect to droplet size (μm), number of droplets per area (cm^2) and droplet deposition ($\mu L/cm^2$). By using SAS v9.4 software, the entire dataset was analyzed for descriptive statistics, analysis of variance (ANOVA) and Tukey significant test. It should be noted that WSPs are less sensitive to droplets smaller than 50 μm, which may lead to underestimation of fine spray deposition. Nevertheless, WSPs are widely used in UAV spray studies due to their practicality, ease of use, and established compatibility with analysis software such as DepositScan.

2.4.6. *Chemical used*

The actual pesticide (Alosa EC) was used at a concentration of 0.5 % w/v in the spray deposition test. Physical properties of the chemical used in the actual experiment namely surface tension, viscosity and density are 34.57 mN/m, 0.94 cP and 0.991 g/ml respectively.

3. Results and discussion

3.1. *Effect of payload and flight speed on deposition characteristics*

Table 2 shows the compilation of significant tests for all depositions. From the results, all deposition

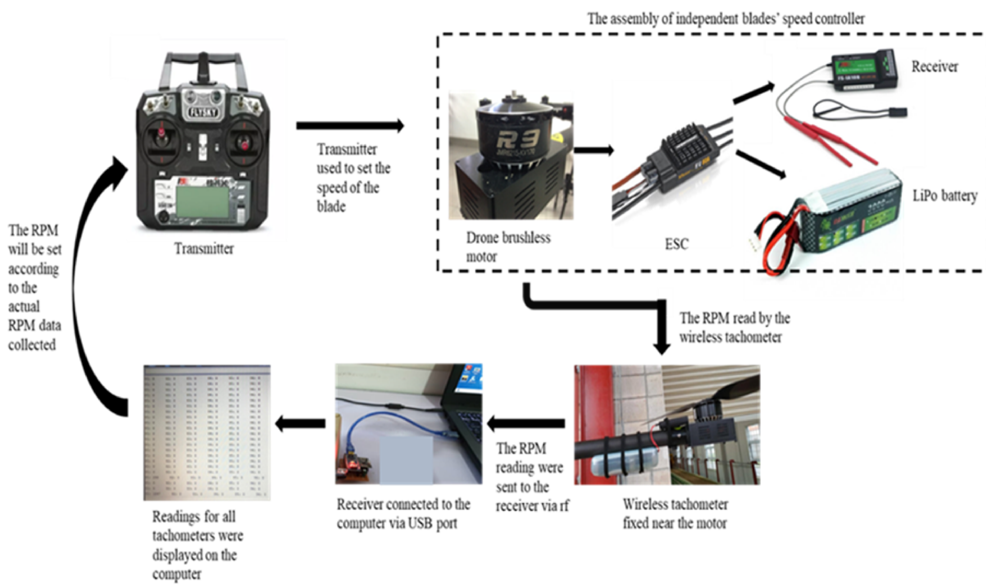


Fig. 5. The process of receiving and setting of the rotors' RPM.

characteristics were significantly influenced by UAV flight speed. Analysis using SAS v9.4 software showed that there is a significant effect on droplet size as flying speed increases (P > F = 0.0416) but not influenced by payload (P > F = 0.7232).

The results in Table 2 indicate that flying speed is more dominant in influencing the size and deposition of the droplets. Based on previous study by Ismail et al. (2021), although the RPM of the rotors were found to significantly change as the payload changes due to the thrust produced, but the airflow produced from the changes in payload does not affect much on the deposition characteristics.

Fig. 6. The UAV was mounted on a facility at a height of 2.5 m from the ground.

3.1.1. Droplet size

The droplets size at 3 m/s flight speed ranged between 318.82 and 384.75 μm, which were then reduced to 274–283.10 μm at 5 m/s and 250.20–294.67 μm at 7 m/s (Table 3). According to ASABE S572.1 standard size of droplet classification, all of the ranges are under medium spray droplets.

Theoretically, liquid that emanates from the nozzle into an ambient air may break up into small drops due to the disturbance caused by air friction from the relative movement between two phases of liquid and surrounding air medium. As the airflow velocity increased, the flat liquid film was gradually increased by the shearing force of air, accelerating droplets deformation rate. At certain critical state where the surface tension is not enough to resist liquid flow, the droplets are continuously stretched causing them to be broken into primary and secondary broken stages, thus producing smaller droplet. However, as depicted from the result, air speed from the downward force produced from the thrust (influenced by payload) was not dominant on droplet size. This might be due to the changing of downwash airflow to vortex as the UAV fly at a certain speed. However, the downwash might affect the droplet size if the UAV was static or during spot spraying (in field).

3.1.2. Number of droplets per unit area (cm^2)

Results show that number of droplets per area significantly reduced as flight speed increased (P > F = <0.0001), while payload did not influence this aspect (P > F = 0.2492). Table 4 shows the droplet deposition data per area (cm^2) collected,

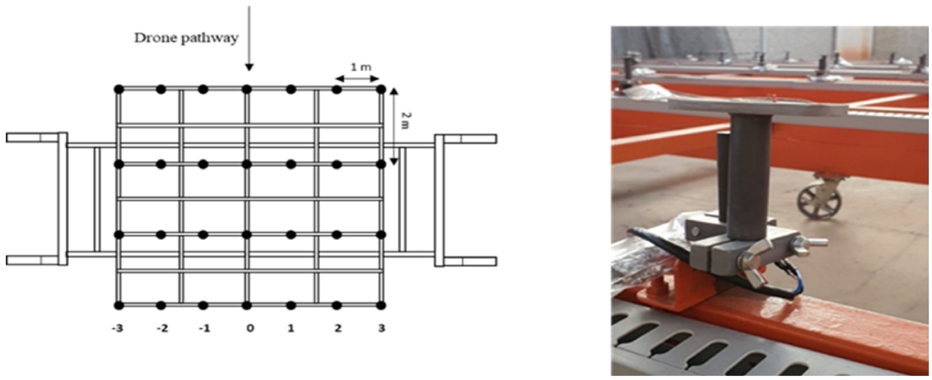


Fig. 7. Water-sensitive papers were fixed at the sampling points on the sampling platform to measure the distribution of droplet deposition.

Table 2. Relationship between deposition characteristics with UAV payload and flight speed.

Source of variation	Deposition characteristics		
	Droplet size (μm)	Number of droplets per area (cm^2)	Deposition rate (μL/cm^2)
Payload	0.7273	0.2492	04897
Flight speed	0.0416*	≤0.0001***	≤0.0001***

Variables of Significant (*p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001) based on Tukey significant test.

Table 3. Mean, standard deviation and CV values of droplet size at various flight speeds and payloads (μm).

Payload	Flight speed		
	3 m/s	5 m/s	7 m/s
3.3	329.30 ± 65.26 : 19 %	277.40 ± 83.84 : 30 %	250.20 ± 62.82 : 25 %
6.6	318.82 ± 70.49 : 22 %	283.10 ± 93.79 : 33 %	256.70 ± 47.62 : 19 %
9.9	348.75 ± 83.49 : 24 %	274.00 ± 56.21 : 21 %	294.67 ± 84.71 : 29 %

Table 4. Mean, standard deviation, and CV values of droplet deposition at various flight speeds and payloads (droplets/cm^2).

Payload	Flight speed		
	3 m/s	5 m/s	7 m/s
3.3	52.46 ± 11.72 : 22 %	19.79 ± 8.10 : 41 %	18.7 ± 8.62 : 46 %
6.6	41.56 ± 9.93 : 23 %	19.05 ± 6.45 : 34 %	17.26 ± 9.54 : 55 %
9.9	57.54 ± 22.07 : 38 %	21.64 ± 8.14 : 38 %	18.6 ± 3.36 : 18 %

ranging between 41.56 and 57.54 droplets/cm^2 at 3 m/s, 19.05 to 21.64 droplets/cm^2 at 5 m/s and 17.26 to 18.7 droplets/cm^2 at 7 m/s.

3.1.3. Deposition rate (μL/cm^2)

Size of droplets (μm) and number of droplets per area (droplets/cm^2) will determine the amount of deposition per area (μL/cm^2). Thus, the reduced pattern size and number of droplets per area would give the same pattern towards the amount of deposition per area (μL/cm^2). Analysis using SAS software in Table 5 shows that the deposition was significantly affected by flying speed. The deposition ranges from the average of 0.30–0.46 μL/cm^2 at 3 m/s, 0.13–0.15 μL/cm^2 at 5 m/s, and 0.10–0.11 μL/cm^2 at 7 m/s. High CV values (>70 %) variability for some of the data is likely due to droplet coalescence on WSPs and DepositScan sensitivity limits.

For number of droplets per area and deposition rate, lower flying speed recorded higher deposition and vice versa. These results tally with finding by Martin et al. (2019) who stated that UAV flying speed strongly affect deposition compared to other factors such as flying height. Higher deposition at lower flying speed is expected as it will increase droplet penetration due to strong downwash of air created by rotors rotation. Finding on effect of flying speed towards deposition is also parallel with simulation done by Wen et al. (2019), which found that as the flying speed of UAV increases (1–7 m/s), wake flow behind the fuselage exhibited a spiral

Table 5. Mean, standard deviation and CV values of droplet deposition at various speeds and payloads (μL/cm²).

Payload	Flight speed		
	3 m/s	5 m/s	7 m/s
3.3	0.37 ± 0.17 : 47 %	0.15 ± 0.10 : 66 %	0.10 ± 0.07 : 74 %
6.6	0.30 ± 0.18 : 58 %	0.13 ± 0.09 : 71 %	0.10 ± 0.07 : 80 %
9.9	0.46 ± 0.26 : 57 %	0.13 ± 0.08 : 59 %	0.11 ± 0.07 : 57 %

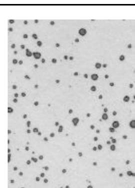
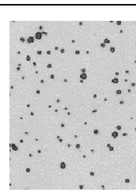
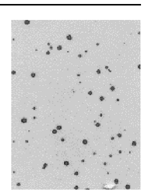
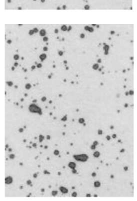
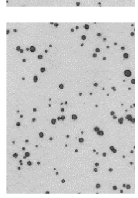
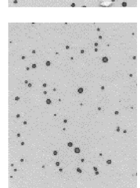
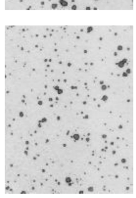
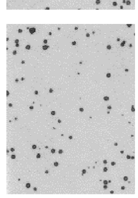
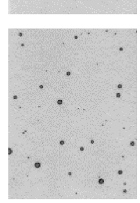
horseshoe vortex and become more incline upward at corresponding pitch angles that also increase (1–7 deg). The horseshoe vortex has been found sufficient to suck up numerous droplets and has a greater influence on droplet entrainment. The inclined flow field resulted in velocity value of the flow field near the ground decreases, which would indicate that the penetration effect of droplets decreases with increase in UAV flight speed.

Besides being entrapped in the vortex, another reason to add is the possibility that smaller droplets aloft on the air when the UAV passes the spray zone, resulting the droplets to drift away and not being deposited on the target, thus reducing deposition. This is also mentioned by Li et al. (2021), where bigger droplet sizes have higher droplet velocity and less prone to displacement by wind.

3.1.4. Simulation of deposition pattern during travelling

Table 6 shows the deposition pattern based on the sample collected at each combination of flight speed and payload. Visually, intensity of the spray pattern was found to be reduced with higher flying speed, which is tally with the deposition rate quantified in Table 6.

Table 6. Deposition of droplets at different payloads and flight speeds.

Payload (kg)	Flight speed (m/s)		
	3 m/s	5 m/s	7 m/s
3.3			
6.6			
9.9			

Ismail et al. (2021) found that, along its path, UAV flight speed during accelerating and decelerating phases were not constant and lower than the set flight speed. Based on the findings, speed transition curves showing UAVs only maintained set speeds for 27.45 % of travel distance. Finding from this study gave a clearer picture and comply with hypothesis listed in Ismail et al. (2021) that the deposition of droplets would not be uniform.

If this deposition pattern is simulated in the real world, the pattern of deposition is as depicted in Fig. 8. For this simulation, the UAV was set at a flight speed of 5 m/s on a straight path. For accelerating and decelerating phases, the UAV was running at below 5 m/s and was only flying at the set speed at 27.45 % from the total distance travelled (Ismail et al., 2021), and the payload reduced as the UAV is spraying. By using four green nozzles with total flow rate of 2.28 L/min, the time to finish one tank of 10 L (~10 kg) of pesticide is 4.39 min. Thus, for the accelerating, stable and decelerating phases, about 4.6 kg, 2.1 kg and 3.3 kg, respectively, were calculated to be applied. Therefore, the UAV is at the first phase when the tank is at 9.9 kg, second phase when the tank is at 6.6 kg and 3.3 kg at the third phase.

For amount of deposition (μL/cm²), equation generated from the line graph (Fig. 9) based on Table 5 was used to calculate the range of possible deposition amount that falls under each phase. In this study, linear regression between UAV flight speed and droplet deposition produced $R^2 = 1$ (Fig. 9). In statistical terms, this indicates a perfect linear relationship, where 100 % of the variation in droplet deposition is explained by flight speed. In our case, the perfect fit can be attributed to two main factors: (i) the experiment was conducted indoor testing facility under controlled conditions (stable weather, constant spray formulation, uniform operating parameters), which minimized random variability, and (ii) the dataset was limited to a small number of points, which happened to align perfectly within the studied range. It is found that for the accelerating and decelerating phases, where the speed is below 5 m/s, the range of

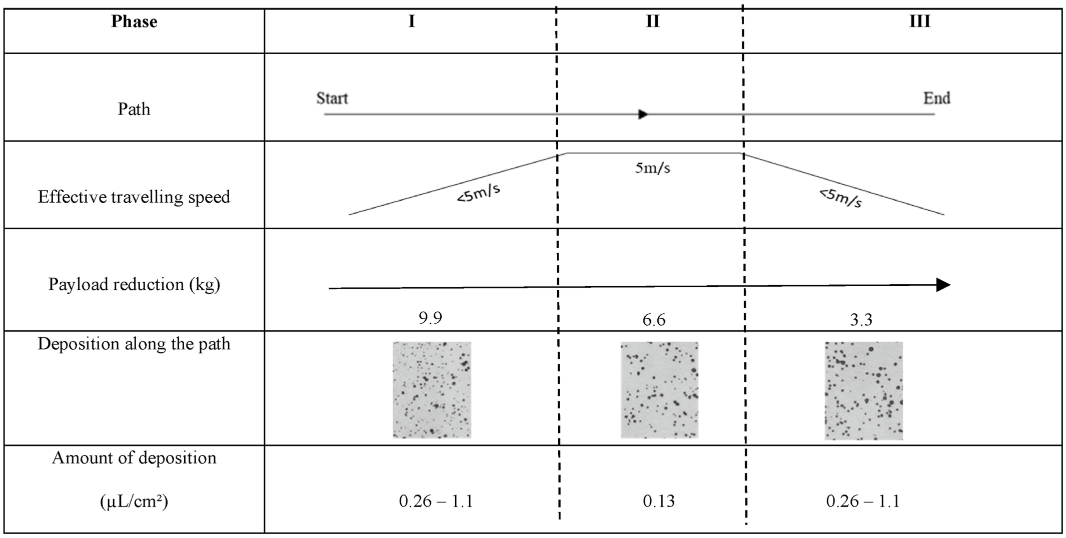


Fig. 8. Simulation pattern of deposition based on travelling pattern of UAV on a straight path. The set flight speed of the UAV is simulated at 5 m/s.

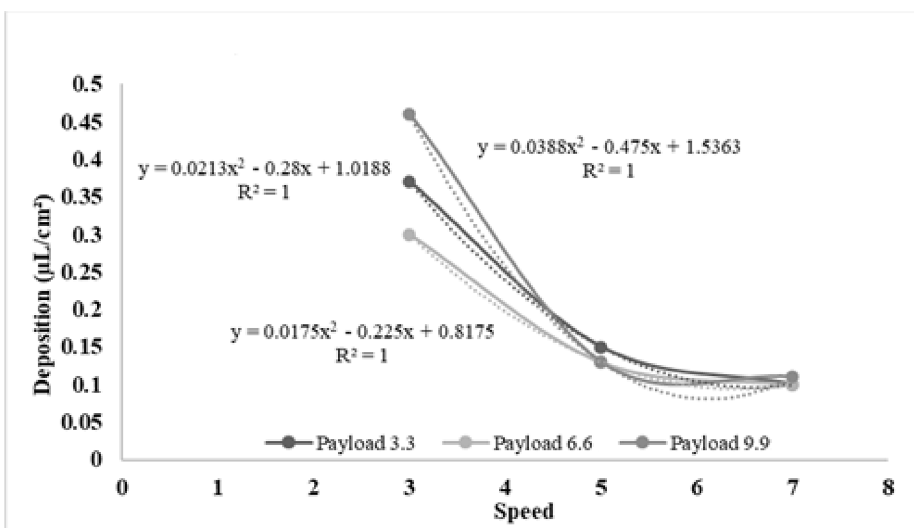


Fig. 9. Line graph of amount of deposition (μL/cm^2) vs flight speed (m/s).

deposition is between 0.26 and 1.1 μL/cm^2. While at the stable phase which is at the set flight speed of 5 m/s, the amount of deposition is approximately 0.13 μL/cm^2. The amount of deposition applied during accelerating and decelerating were found to be 2–8.5 times higher compared to the amount of deposition at stable phase.

Result confirming UAV flight speed having dominant effect on droplet deposition compared to payload complements earlier findings on the influence of rotor airflow in causing uncontrolled multi-directional droplet drift, which consequently alters deposition patterns and leads to pesticide waste (Wang et al., 2017; He et al., 2017; Zhang et al., 2017). This observed non-uniform application may also provide a possible explanation for previous reports that UAV spraying often resulted in low precision and unsatisfactory deposition in both lateral and longitudinal directions along the flight path (Hanxin, 2016; Qin et al., 2016; Shilin et al., 2017). Aside from environmental conditions, spray chemicals used, leaf properties, spray system and working nature of UAV during spraying would also need to be studied to provide better understanding of how the technology works and how it affects spraying efficiency and improve the overall application of the technology.

4. Conclusion

This study has experimented on the behavior of UAV during operation with various payloads and flight speeds to determine the size and deposition of the droplets.

- The study discovered that only UAV speed had significant effect on droplet size and deposition. As the UAV moved faster, the droplet size reduced from 318.8 to 384.7 μm at 3 m/s to 250.2−294.7 μm at 7 m/s, while number of droplets deposited were reduced from 41.56 to 57.54 droplets/cm^2 at 3 m/s to 17.26 to 18.7 droplets/cm^2 at 7 m/s, and deposition rate decreased from 0.30 to 0.46 μL/cm^2 at 3 m/s to 0.10−0.11 μL/cm^2 at 7 m/s. The study also found that payload has no significant effect on droplet size and deposition.
- The study found that due to the nature of UAV travelling pattern dynamics, the flight speed was not uniform in the acceleration and deceleration phases, thus resulting in non-uniform droplet deposition. Based on the simulation done, the amount of deposition applied during accelerating and decelerating were found to be 2−8.5 times higher compared to the amount of deposition at stable phase.
- This experiment was conducted indoors without being disturbed by wind; therefore, the deposition non-uniformity might be worse if affected by wind.

Therefore, based on these conclusions, there are few solutions that might be worth considering. Technically, the first solution could be in the selection of the rotors. The use of more smaller rotors compared to less bigger rotors might be useful in order to get the set flight speed. Although it might affect the UAV's stability, it can minimize deposition variation in the accelerating and decelerating phases. The second solution is by using variable rate sprayer that can be synchronized with the speed of the UAV. Lastly, addition of relevant chemical solution can be used as ‘drift reduction technology’ to reduce the potential of droplet drift.

5. Future work

In this study, airflow strength was estimated indirectly from rotor RPM, which may oversimplify the complex downwash interactions between rotors, droplets, and crop canopy. To improve accuracy, future studies should integrate Computational Fluid Dynamics (CFD) simulations or experimental flow visualization techniques such as Particle Image Velocimetry (PIV) to better characterize airflow dynamics and their effects on droplet deposition. Furthermore, the result of deposition from indoor test should be compared with actual test under the same setting, so that the error from these results could be used in model calibration and validation, eventually enhancing the reliability of deposition predictions in actual field conditions.

Declaration of generative AI and AI-assisted technologies in the writing process

We declare that no Artificial Intelligence (AI) technologies or AI-assisted tools were utilized in any capacity during the writing and preparation of this article.

Ethics information

This study did not involve human participants or animals, and no specific ethical approval was required.

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Conflicts of interest

The author(s) declare(s) that there is no conflict of interest in the publication of this paper.

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